Glacier (and ice sheet) Mass Balance

The long-term average position of the highest (late summer) firn line is termed the **Equilibrium Line Altitude (ELA)**

Firn is old snow
How an ice sheet works (roughly):

Why is the **NH insolation** important for **global ice sheet advance** (Milankovitch theory)?

**Why focus on summertime?**
Ice sheets are very sensitive to summertime temperatures!

- Ice sheet has parabolic shape.
- Line represents melt zone.
- Small warming increases melt zone (horizontal area) a lot because of shape!
Influence of shape

Furthermore temperature has a powerful influence on melting rate.
Temperature and Ice Mass Balance

Summer Temperature main factor determining ice growth

e.g., a warming will
Expand ablation area, lengthen melt season, increase the melt rate, and increase proportion of precip falling as rain
It may also bring more precip to the region

Since ablation rate increases rapidly with increasing temperature
- Summer melting controls ice sheet fate*
- Orbital timescales - Summer insolation must control ice sheet growth

*Not true for Antarctica in near term though, where it’s too cold to melt much at surface
Temperature and Ice Mass Balance

Rule of thumb is that 1°C warming causes an additional 1m of melt (see slope of ablation curve at right)
Equilibrium Line vs Latitude

Assuming the atm. temperature decreases with height and as you go north, the equilibrium line should rise for more southern latitudes.
Ice Elevation Feedback

As ice sheets grow vertically ELA in same location but ice moves relative to it
- more ice surface area is above the ELA
- Promotes accumulation

Positive feedback
Bedrock Feedback

Delayed bedrock sinking during ice accumulation keeps icesheet at higher elevation during expansion

Delayed bedrock rebound during ice melting keeps icesheets at lower elevation during collapse

Positive feedback when considered with previous FB
If bedrock were to lower quickly during ice advance, ice would populate lower altitude and minimize the ice-elevation FB. Hence a short time constant for bedrock response reduces the ice-elevation feedback.

Homework 3 will have you test this idea in an EBM with an ice sheet.
Figure 3. Cross sections of ice sheet, sediment (solid), and bedrock (stippled) at two different times from the run in Figure 2a. Although the linear north-south extents are the same at the two times, there is still sediment under much of the ice sheet during the earlier time so the ice sheet is relatively thin and the bedrock depression is shallow. In contrast, during the later time, there is no sediment remaining under the ice sheet so the ice sheet is thicker and the bedrock depression is deeper.
Methods of measuring mass balance

Stratigraphic Method

Above firn line (snow line), dig pit to identify annual layer.

End of melt season is reasonably well defined. Identifies net mass balance locally

May also leave stakes in place at end of melt season and take snow height reading at beginning of next melt season. Identifies winter mass balance.

Summer mass balance is the difference
Methods of measuring mass balance

Fixed-year Method

Measure at fixed times of year using “water cycle year”, beginning at approximate end of melt season/beginning of accumulation season (roughly October). Melt season begins at roughly May. Dates do not vary at a given glacier, but may vary from glacier to glacier.

Use stakes, GPS, or cameras to measure annual winter accumulation (Oct 1 - Apr 31, typ.) annual summer ablation (May 1 - Sep 31, typ.)
Marshall 2006

net balance = accumulation - ablation

\[ \dot{b} = \dot{a} - \dot{m} \]

rates in m/yr or kg/m²/yr
A. Accumulation

accumulation = fraction of precip that falls as snow times precip

\[ a = \phi_s P \]

where each is a function of location, but not time

\[ \phi_s \text{ could be } \begin{cases} 
1 & \text{if } T < \text{arbitrary threshold, } T_t \\
0 & \text{if } T > \text{arbitrary threshold, } T_t 
\end{cases} \]

but only works well if surface temp. T is known at a high frequency, like 4X daily or better
If instead a monthly mean $T$ is known ($T_m$) and it is distributed roughly as a gaussian:

$$\phi_s = \frac{1}{\sigma_m (2\pi)^{0.5}} \int_{-\infty}^{T_t} \exp\left[ - \frac{(T-T_m)^2}{2 \sigma_m^2} \right] dT$$

$\phi_s$ = fraction of time $T < T_t$

$\sigma_m$ = standard deviation of hourly $T$

Known as a degree day methodology (in this case negative)
B. Ablation

Energy Balance Method

\[ \rho L \dot{m} = F_{sw} (1-\alpha) + F_{lw} + F_s + F_l - F_c - F_{p,r} \]

- \( F_{sw} (1-\alpha) \) = net absorbed shortwave
- \( F_{lw} \) = net downward longwave
- \( F_s \) = sensible heat flux
- \( F_l \) = latent heat flux
- \( F_c \) = conductive flux into ice or snow
- \( F_{p,r} \) = advective energy by precipitation and runoff
- \( L \) = latent heat of fusion
- \( \rho \) = density of snow or ice

If \( T < \) melting temperature, then zero left hand side and solve right hand side for surface temperature
Generally models have errors too large and observations can be inadequate to give accuracy needed. An alternative is the Positive Degree Day method:

Integrated melt \( m(\tau) \) in time \( \tau \)

\[
m(\tau) = d_{S/I} \cdot \text{PDD}(T)
\]

\( d_{S/I} \) is the degree day (fudge) factor

\[
\text{PDD} = \int_0^\infty T \cdot \text{pdf}(T) \, dT = \frac{\tau}{\sigma_m (2\pi)^{0.5}} \int_0^\infty T \exp\left[-(T-T_m)^2/(2\sigma_m^2)\right] \, dT
\]

works well for monthly data, \( \tau \) is the length of month in days
C. Ablation also includes calving, ocean-ice melt, sublimation, basal melt

often calving is treated crudely by chopping off ice on the ocean that is thicker than a threshold.

Another strategy has been to parameterize it

\[ \dot{m}_c = k_o \exp\left[\frac{(T - T_o)}{T_c}\right] H H_w \]

\( H = \) ice thickness
\( H_w = \) water thickness

the parameterization is designed to make calving rates depend on temperature
Elsberg et al 2001
Mountain glacier schematic

looks like tilted bicycle seat

illustrates nicely nonlinearity of area and volume change for mountain glacier

Note $\Delta V$ includes effects of flow

Fig. 1. Schematic of a glacier which has advanced since the reference surface was defined. $A'$ is the map area of the reference surface; $\Delta A$ is the change in map area due to advance; $\Delta V$ is the increase in volume; $Z$, $Z'$ and $Z_r$ are the elevations of the conventional, reference and bedrock surfaces, respectively.
Response times depend on (see Marshall 2006)

• the size of the ice mass
• the dynamic and thermodynamic regime
• topographic environment
• climatic environment

Simplified view of glacier dynamics can offer estimate of response time

\[ \frac{dV}{dt} = H \frac{dA}{dt} \]
South Cascade Glacier

Global Warming or recovery from Little Ice Age?
Fig. 3. Decreasing glacier area with unweighted best-fitting straight line. Data from 15 sources.
Harrison et al, 2001  South Cascade Glacier

dV/dA = H \sim 7 \text{ m} \ “\text{thickness scale}” (\text{slope of data})

\dot{b}_e = -6.2 \text{ m/yr}

\dot{G}_e = \frac{\text{db/dz}}{\text{yr}} \quad = 0.024 \text{ /yr}

Together these give a scaling law for timescale of mass balance change

\tau_v = \frac{1}{(-\dot{b}_e/H - \dot{G}_e)}

\tau_v = 82 \text{ yrs}
Figure from RealClimate.org probably made by Eric Steig
Pollard 2000

Greenland mass balance terms from IPCC models

energy balance method

PDD method

\[ P = \text{Precipitation} \]

\[ A = \text{Ablation (greater scatter)} \]

\[ N = P - A \]
Pollard 2000

Precip rate in cm/yr
Pollard 2000

Melt rate in cm/yr
Pollard 2000

Ice Sheet elevation (m) from off line ice sheet model run with climate model output after 10k years initialized to present day for Greenland and reconstruction for Laurentide